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NUCLEAR SURVIVABILITY/VULNERABILITY OF AIRCREWS: AN EXPERIMENTA--ETC(U)
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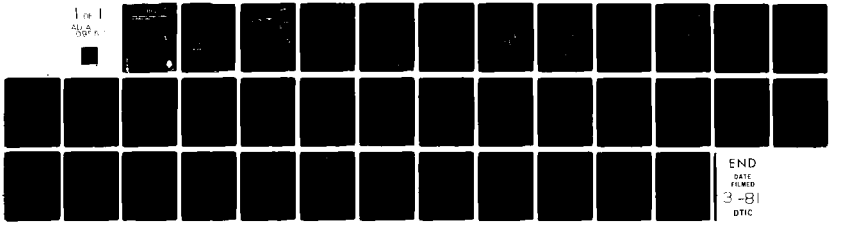

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NUCLEAR SURVIVABILITY/VULNERABILITY OF AIRCREWS: AN EXPERIMENTAL APPROACH

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January 1981

Final Report for Period January 1977 - September 1980

Approved for public release; distribution unlimited.

USAF SCHOOL OF AEROSPACE MEDICINE
Aerospace Medical Division (AFSC)
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NOTICES

This final report was submitted by personnel of the Weapons Effects Branch, Radiation Sciences Division, USAF School of Aerospace Medicine, Aerospace Medical Division, AFSC, Brooks Air Force Base, Texas, under job order 7757-05-37.

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The animals involved in this study were procured, maintained, and used in accordance with the Animal Welfare Act of 1970 and the "Guide for the Care and Use of Laboratory Animals" prepared by the Institute of Laboratory Animal Resources - National Research Council. Additionally, the animals used in this study met the USAFSAM policy criteria established 1 February 1978.

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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The complexity of modern manned-weapons systems requires maximal operator proficiency to insure mission success. This experiment was designed to determine, using trained subhuman primates, the effects of ionizing radiation upon tracking and discrete-avoidance behavior. During exposure to ^{60}cobalt gamma radiation given in divided doses over 7½ hours, the monkeys performed Multiple Alternative Reaction Time (MART) tasks and on the Primate Equilibrium Platform (PEP). Testing at two radiation levels is reported: a high-dose total of 1,440 rad (14.4 Gy) and a low-dose total of 360 rad (3.6 Gy). Testing and observation were done

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20. ABSTRACT (Continued)

for a total of 10 hours on the day of irradiation for both radiation levels and on the day following irradiation for the high-dose level only.

All high-dose subjects (six) displayed significant performance decrement in some aspect of testing on the day of exposure. Performance on the following day continued to show decrement, though generally much less than on the exposure day. In the low-level exposure phase, all subjects (four) also displayed significant decrement in at least one performance parameter. However, this group did not appear to be as severely affected as the high-exposure group. All subjects in the high-exposure group had retching activity some time during the exposure-day testing period; five of the six had productive emesis. No retching or emesis occurred later or in the low-dose exposure group. Decision-making events, as depicted by MART testing, were more severely affected than was the continuous PEP task. The response times for the MART test were significantly slowed, especially in the high-dose exposure group. Therefore, especially as depicted in the high-exposure group during radiation exposure and for a few hours after, members of aircrews should expect that performance decrement in rapidly interpreting and applying information would be severe enough to make mission completion improbable.

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NUCLEAR SURVIVABILITY/VULNERABILITY OF AIRCREWS: AN EXPERIMENTAL APPROACH

INTRODUCTION

An essential part of a modern strategic bomber's capabilities is its nuclear survivability, defined as "The capability of the system required to accomplish the designated mission in the presence of nuclear environments created by direct enemy attack or from collateral effects of a nearby nuclear detonation" (AFR 80-38). This survivability depends upon both the aircraft and its aircrew maintaining mission-completion performance during and after exposure to nuclear environments. Therefore, radiation-induced problems in crew responses must be considered in overall system survivability/vulnerability (S/V) analyses.

In an aircraft that withstands thermal and blast damage, other nuclear phenomena either pose little threat to the totally enclosed crewmember or can be reasonably countered by protective devices. The ionizing radiation component of a nuclear detonation is of most concern to crew S/V analysts. Nuclear radiation is not easily countered because of its ability to penetrate matter and thus act directly upon the tissues of crewmembers.

Modern systems require highly trained operators whose performance is routinely subjected to various stresses. The addition of ionizing radiation may degrade the operator's performance capability, thereby threatening the survivability of an otherwise functional system. Even sublethal radiation doses can cause nausea, fatigue, and emesis; larger doses may produce temporary periods of incapacitation during which meaningful performance is questionable, if not impossible.

The experiment reported herein was designed to predict the performance of a bomber pilot engaged in a 10-hour mission. Certain operational flight tasks were simulated in the laboratory to increase the relevance of the data.

In addition to recording and analyzing the quantitative measures of performance, we made clinical observations on monkeys before, during, and after irradiation, thus gaining additional insight into the effect of radiation upon the performance of the subjects. These data should be valuable to crew S/V analysts and others involved in planning strategic and tactical missions.

EXPERIMENTAL METHODOLOGY

Meaningful and timely results from an experimental modeling effort depend strongly upon the modeling techniques used, the data collection and preprocessing approach, and the data analysis procedures. Because these factors are critical, they, along with supporting rationale, will be discussed in detail. This discussion should provide insight into the experimental modeling approach, as well as a basis for assessing the applicability of experimental findings to a specific situation.

Subjects

Six naive monkeys (*Macaca mulatta*) weighing between 3.6 and 4.8 kg were selected as subjects (Ss) for Phase I of this experiment, and four naive monkeys (*Macaca mulatta*) weighing between 3.5 and 4.2 kg were selected for Phase II. This species is physiologically (anatomically) similar to humans, possesses similar digital manipulative capabilities, can be trained to perform complex tasks, and is relatively easy to handle.

Apparatus

The Primate Equilibrium Platform (PEP) was selected as the primary apparatus in this experiment because a monkey's control of the PEP is similar to pilot control of an aircraft (7). The PEP has been used to demonstrate changes in behavior as a function of both single and multiple radiation pulses (1, 2). Its response characteristics to control-stick movement are similar to those of an aircraft, both being rate controls. The PEP consists of a gimballed platform perturbed from the horizontal by an input forcing function that simulates rough air. The subject compensates for these perturbations by manipulating a control stick (Fig. 1).

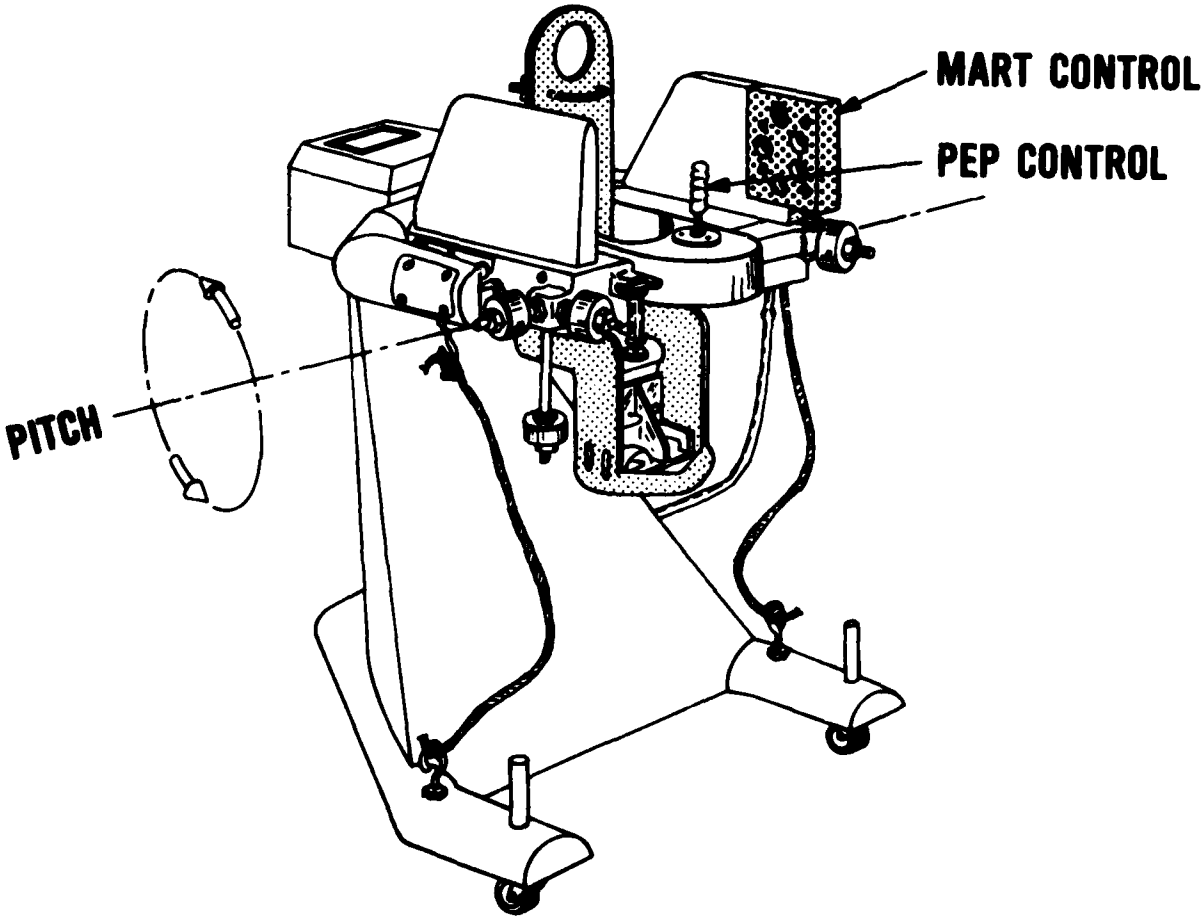


Figure 1. PEP/MART equipment.

To provide additional similarity to actual pilot workload, we added a discrete task. This task, the Multiple Alternative Reaction Task (MART), incorporates a yellow cue light (alert), an audible cue (a 1000-Hz tone), and four red cue lights (fire), arranged as shown in Figure 2. The illumination of the yellow light (which was accompanied by the audible tone) was a cue

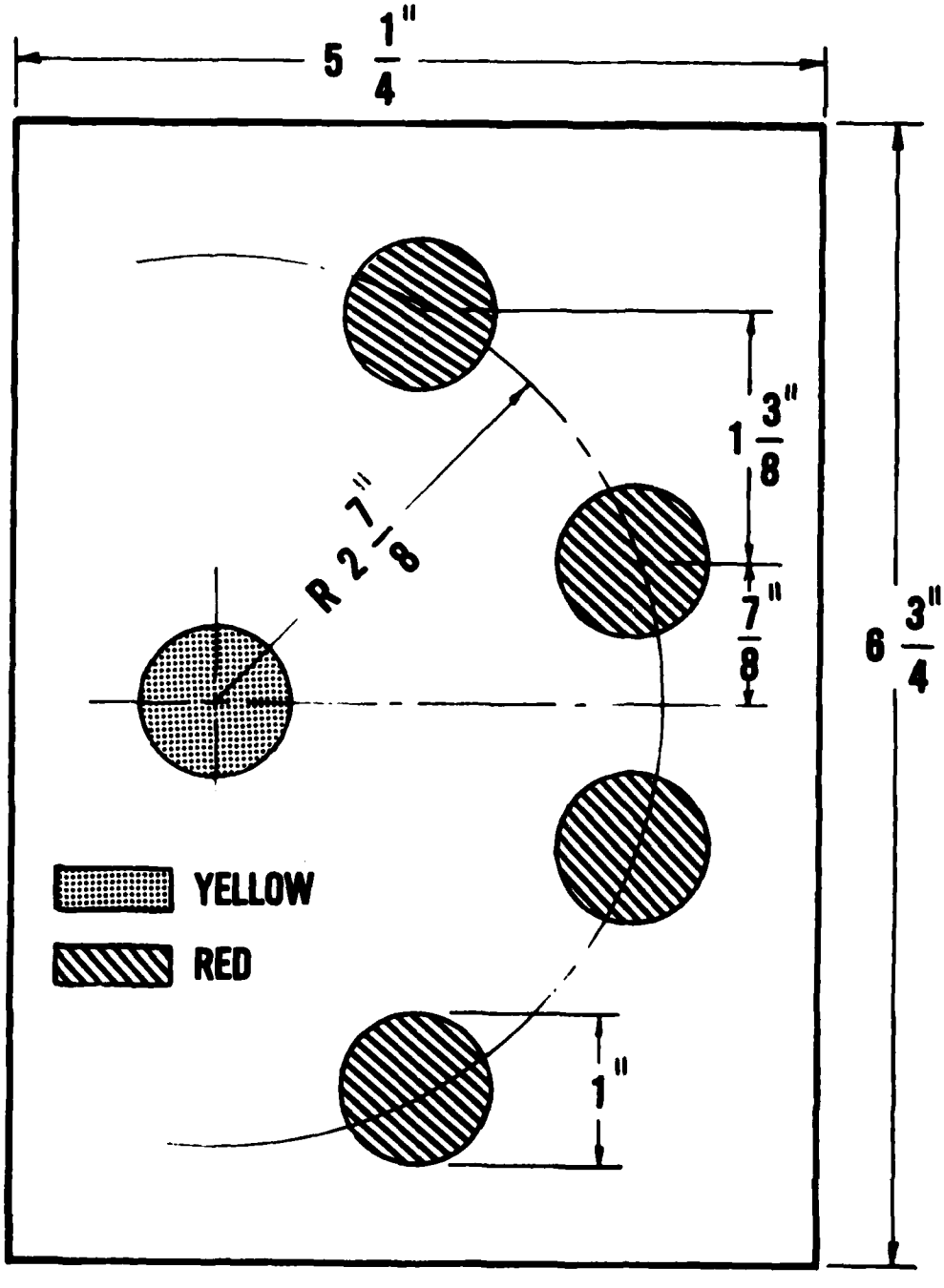


Figure 2. Front view of the MART apparatus.

for the subject to touch the NESA glass face of the light, thereby extinguishing it. A correct response was immediately followed by the random (balanced) illumination of any one of the four red cue lights, also requiring a touch to extinguish. The combined PEP/MART is shown in Figure 1. The MART is mounted to the front and left of the subject.

The PEP/MART was used in this study to simulate aircraft control and operator response to a master caution/warning light and four engine-fire lights. Such cockpit tasks require both continuous and discrete operator responses. The monkey must be highly motivated to perform these tasks with maximum precision, and this motivational state must be maintained over the entire experimental session (in this case, 10 hours) so that an accurate performance decrement estimate can be obtained. The motivation of the subjects was maintained using established avoidance-conditioning methodology; i.e., the subjects received a mild electric shock to the feet upon (1) allowing the PEP to deviate 10 degrees from the horizontal, (2) failure to respond, or (3) responding incorrectly to the MART lights. Avoidance motivation was maintained over the entire 10-hour day and resulted in very stable performance.

In addition to simulating aircraft control and operator response to warning lights, we made an effort to simulate missions that contain basic flight segments of takeoff, climbout, cruise, refuel, and penetration. Because each mission segment varies with respect to workload and task complexity, we attempted to simulate these schedules over a hypothetical 10-hour mission.

The forcing-function input to the PEP was a white-noise signal intended to simulate atmospheric turbulence which can be mathematically characterized by the Dryden spectral approximation used as an Air Force standard.

Schedule and Selection of Radiation Parameters

Subject workload and task type considered for each mission phase are shown in the top line of Figure 3. Note that PEP control is indicated during takeoff, climbout, aerial refueling, and penetration because the pilot normally exercises manual control of the aircraft during these maneuvers. A PEP control segment was also included in the long cruise phase to account for possible periods of manual aircraft control due to a refueling top-off and/or change in flight.

The MART was operational (six trials per minute) during the latter phases of each of the PEP sessions and throughout penetration to simulate added workload of the Air Force systems operator at these critical time periods. During cruise, use of MART alone simulated the lower activity level of the pilot. A rate of six trials per minute was used for the first 30 minutes after a PEP session, followed by periods where the rate was decreased to three trials/minute--approximating the lower activity levels during cruise.

Beyond the selection of differential rates of trial presentation, 4- and 5-second response time limits were respectively selected for the yellow and red cue lights to simulate discrete task parameters.

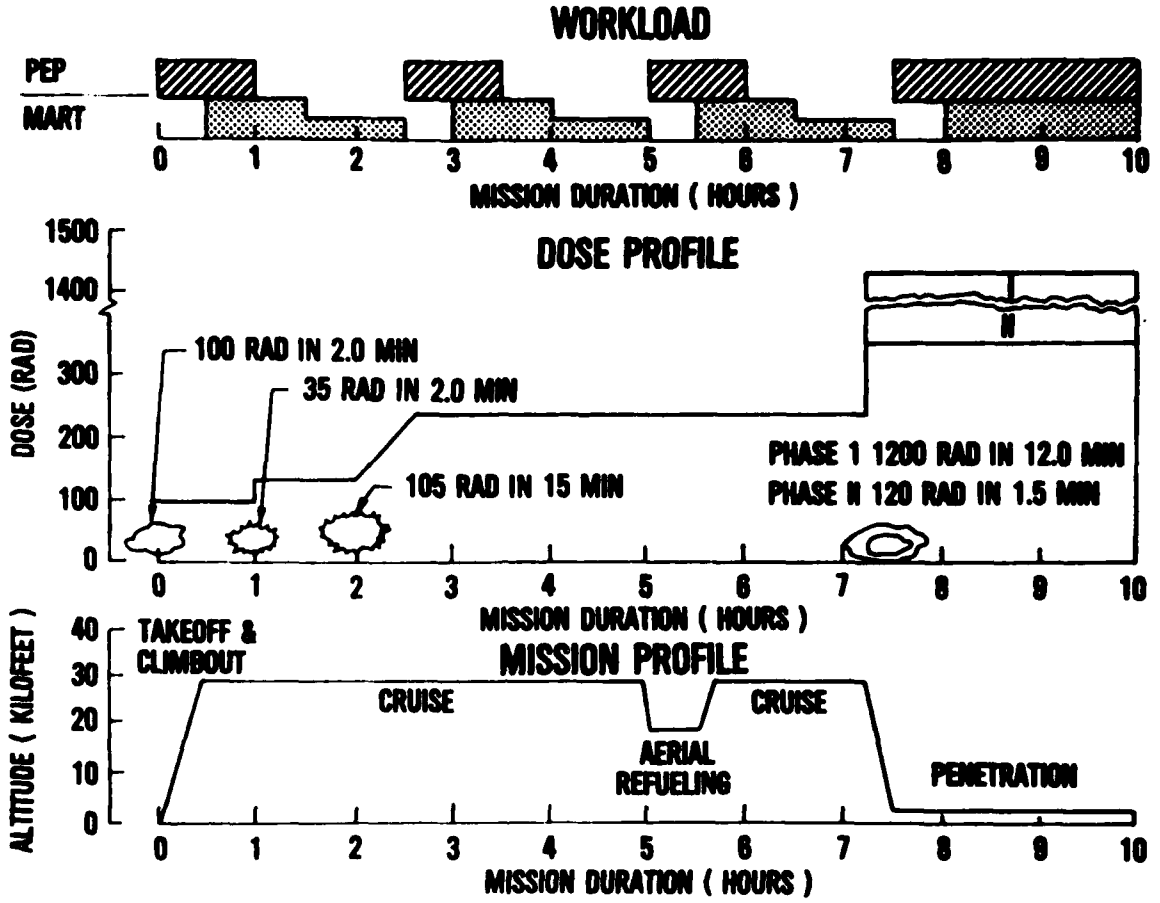


Figure 3. Graphic description of workload to illustrate relationship to radiation exposure and mission profile.

The middle line of Figure 3 depicts the ionizing dose profiles used in this experiment. The dose profiles were developed after personnel of the Strategic Air Command and the USAF School of Aerospace Medicine (USAFSAM) considered several hypothetical nuclear threats that might be encountered during a strategic mission. The dose at takeoff could accrue from detonation of a submarine-launched ballistic missile (SLBM); the dose at 1 hour, from a radioactive cloud; and the dose at 2 hours, from penetration of a residual cloud resulting from an earlier attack on our missile fields. Attempting penetration to the target, additional threats of exposure occur by proximity of surface-to-air or air-to-air missiles. The difference leading to Phase I and Phase II testing was developed around the proximity of this defensive missile attack. The large exposure in Phase I would result from a near miss at about 7½ hours into the mission. The less severe exposure of Phase II would be anticipated at this same time.

The total midline dose to a hypothetical crew over the 10 hours for Phase I would be 1440 rad (14.4 Gy). This dose, if administered acutely, is supralethal to humans and would result in death within a week to 10 days (8). However, the effect of such a large but divided dose on short-term performance (i.e., mission completion and operator performance during poststrike mission) is not expected to be as severe as a single-pulse dose and is also a function of when in the mission the dose is received. The total midline dose for the hypothetical crew over the 10 hours for Phase II would be 360 rad (3.6 Gy). This dose, if administered acutely, would result in death in 30 days for approximately 50% of those exposed (8). The effect of this divided dose to mission completion was expected to be less than the Phase I profile. Prior research documented the effects in monkeys of higher doses of ionizing radiation (4, 10, 13) as well as of lower doses protracted over 72 hours (5, 12).

Procedure

The monkeys were trained on PEP and MART, using standard operant techniques. Initial training was conducted until the subjects met minimal task requirements, at which point proficiency training was begun to allow the subjects to achieve performance stability as the workload was escalated to the identical parameters of the exposure day. Once the subject's performance was reasonably stable, formal baseline procedures began.

Phase I. During the baseline Phase I sessions, data were taken and used to define normal, or preexposure, performance. A total of seven 10-hour baselines were conducted. Two PEP/MART machines were used in this period, but only one was used to establish the normal performance standard in order to maintain consistency over time. Subjects in the alternate PEP/MART were essentially maintaining proficiency. The subjects were worked every third day (excluding weekends) in order to maintain stable performance over the duration of the experiment.

Exposure conditions were identical to the preexposure baseline conditions except that the subjects wer irradiated. Similarly, on various days following irradiation, additional 10-hour performance evaluations were conducted. However, only on the first day post irradiation were all subjects tested; those results are the ones compared here.

Because the standard baseline procedure involved several days of rest between workdays, the postexposure data could have included an extra fatigue factor caused by lack of rest (only 12 hours instead of several days). Therefore, baseline 4 was started the morning after a previous workday (either baseline 3 or a proficiency workday) for each subject. The data from baseline 4 were analyzed to quantify any fatigue effects caused by inadequate rest. This information was then considered in the analysis of the postexposure day, to separate normal fatigue effects and radiation effects.

The monkeys were fed at 0730 and the experiment began at 0830, thus allowing an hour for food and water consumption. This simulates a normal eating schedule for crews. An orange was provided each subject at the end of 5 working hours to provide moisture and nutrition and also simulate the consumption of a flight lunch by the aircrew.

For purpose of data analysis, the 10-hour mission profile shown in Figure 3 was divided into 20 half-hour sessions. Figure 4 depicts this arrangement. During each half-hour session, the subject accomplished a specific set of tasks comparable with the mission phase for that session. In ea session, a few minutes were allowed for setting up the new task, annotating ne experimental log, and reinitializing the computer to collect and preprocess the data.

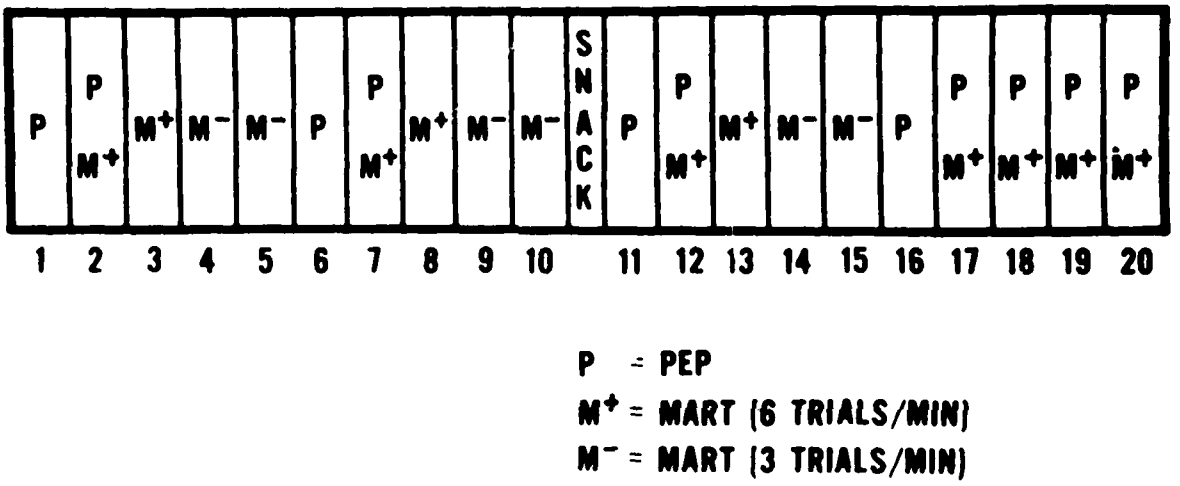


Figure 4. PEP/MART workload for subjects.

Phase II. This phase of the study was accomplished after obtaining the Phase I data, and efforts were made to replicate that study. However, there were some changes: First, the PEP chairs were renovated. Second, the number of baseline tests was changed. Third, the radiation facility was reloaded with a stronger source on 1 September 1978. Fourth, the animals were euthanized the day after their exposure. Hence, no recovery data could be collected, and direct comparisons of the data must include some caution.

Performance Measures

The requirement to objectively define changes in performance caused by exposure to nuclear radiation (or any other stress) necessitates using measures that accurately and reliably reflect subject performance. The continuous PEP control task was used in a recent effort (3), and that data indicated that the

adjusted root mean square (ADRMS), σ, of the instantaneous platform position, P(t), was the better measure of the subjects' average PEP control capability. This variable is defined as:

$$\sigma^2 = \frac{1}{T}\int_0^T \left[p(t)-\mu\right]^2 dt \approx \frac{1}{T}\sum_{t=0}^{T}\left[p(t)-\mu\right]^2$$

where μ is the mean platform position over the time period T (11), or

$$\mu = \frac{1}{T}\int_0^T p(t)dt \approx \frac{1}{T}\sum_{t=0}^{T} p(t)$$

For a more complete discussion of the platform position measurement, see reference 11.

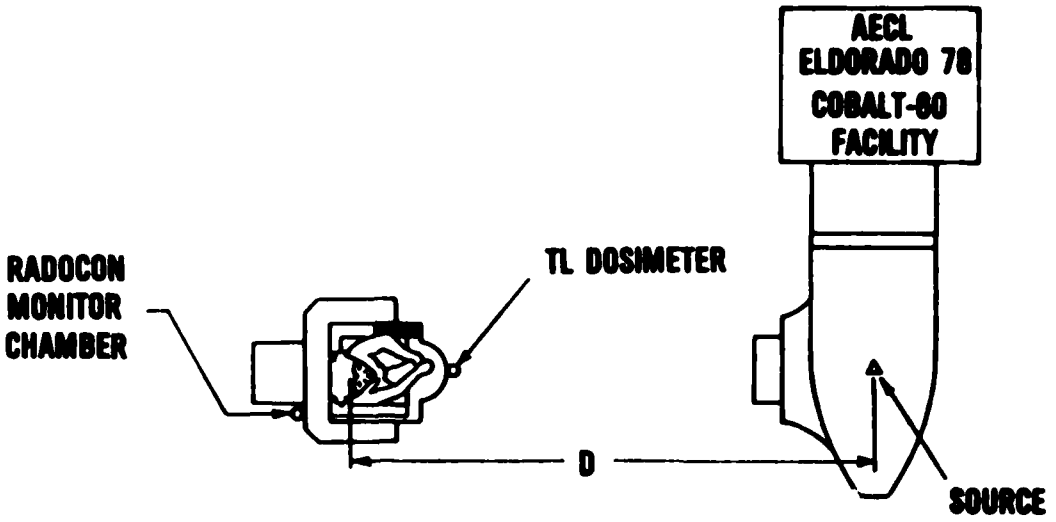
Since the objective of the control task is to maintain a horizontal platform position by compensating for the input forcing function with the control stick, the instantaneous platform position is a key performance indicator. Taking the root mean square (RMS) of this variable over some time yields a representative measure of the subjects' capability to perform the task during that time. For animal subjects, the mean platform position must be subtracted from the instantaneous platform position because the PEP is actually controlled with reference to reinforcement limits rather than to the horizontal position. That is, the experimenter cannot assume a monkey has a concept of "horizontal."

Thus, PEP performance is better reflected by the ADRMS, which is measured with reference to the mean platform position over the time of interest, than by the RMS which uses the horizontal as a reference. As an example, consider a subject maintaining near-perfect control of the PEP (i.e., excellent compensation for the input) but whose mean platform position is 5 degrees. His RMS score would be in excess of 5 degrees. Another subject barely capable of avoiding the 10-degree shock limits but whose mean platform position is zero, may also achieve a RMS score of about 5 degrees. Therefore, subjects whose performance capabilities differ drastically would still have similar RMS scores. Use of the adjusted RMS minimizes this concern.

Dosimetry

The first consideration in establishing dosimetry procedures was to determine the dose profile to be used for the nonhuman primate subjects. The two doses discussed earlier were derived from a hypothetical threat analysis.

Prior to exposure, calculations of exposure configurations needed to achieve the required midline doses and dose rates were performed and verified using instrumented phantoms. These phantoms were constructed of material with the same radiation response characteristics as monkey tissue. The exposure configurations are shown in Figure 5. The animals were exposed anterior-to-posterior, and rates were appropriately administered by varying the chair



		PHASE I		PHASE II	
		DISTANCE (cm)	DOSE RATE (rad/min)	DISTANCE (cm)	DOSE RATE (rad/min)
POSITION I,	SESSION 1	145.6	50	167.7	50
POSITION II,	SESSION 3	246.0	17.5	283.3	17.5
POSITION III,	SESSION 5	388.0	7	477.6	7
POSITION IV,	SESSION 16	105.0	96.1	105.0	144.9

Figure 5. Exposure configuration describing source-to-subject distances for all exposures for Phase I and Phase II.

position at distances from the source. Actual midline doses obtained were estimated to be within $\pm$ 5% of the desired doses. More details of the dosimetry procedures can be found in the appendix.

Data Collection/Preprocessing

The data collection/preprocessing system is based on a PDP-12 digital computer manufactured by Digital Equipment Corporation. The PDP-12 incorporates a real-time clock, 8 channels of analog-to-digital conversion capability, 16K bytes of memory, and a teletype. The instantaneous platform position signals were fed into the PDP-12 and the mean platform position and adjusted RMS of this signal were computed. Sense lines from the MART were also connected to the PDP-12, allowing calculations of response times and accuracies. For the above calculations, each 30-minute session was broken down into 15 two-minute epochs. The epoch scores were calculated, displayed on the CRT display, printed out on the teletype, and also recorded on magnetic tape for more detailed off-line analysis on the IBM 360. The on-line display

was extremely valuable in monitoring animal performance: it insured that equipment and subjects were functioning adequately and served as a backup source of basic data in the event of data loss or scramble in the IBM 360.

The stick position, platform position, and input signals were also recorded on a Sangamo Model FM tape recorder for subsequent frequency analysis.

RESULTS

Statistical Observations

Data obtained from all tests (baseline, radiation exposure, and followup for Phase I, and baseline and radiation exposure for Phase II) are shown in graphic form in Figures 6 through 11. There were seven baselines per animal in Phase I and four in Phase II. Test results on exposure and followup days are identified by unconnected points.

The results of baseline 4 (simulated fatigue test) were essentially unchanged from those of other baselines. Therefore, this baseline was incorporated as one of the seven.

A repeated-measurements analysis of variance (ANOVA) was used to analyze the PEP (adjusted RMS) and MART (alert and fire reaction times) data for each subject separately, using the session data for either PEP only, PEP and MART, or MART only. See Table 1 for the sources of variation considered in the ANOVA where baseline, radiation, and recovery are referred to as treatments. The sources of variation of most interest were treatment-by-session interaction and treatments. The significant interaction reflects that the patterns of the session means are different among the treatments. This could mean that the pattern of baseline session means (averaged over the seven runs) differs from the pattern of session means for the radiation level. At any rate, when this interaction is significant, further testing among the treatment means at different sessions is necessary. If this interaction is not statistically significant, then we can draw conclusions from the treatment main effect.

TABLE 1. SOURCES OF VARIATION FOR REPEATED-MEASUREMENTS ANALYSIS OF VARIANCE

Source	Degrees of freedom
Among treatments[a]	2
Among baseline-run means	6[b]
Among sessions	S-1[c]
Interaction between treatments & sessions	2(S-1)
Interaction between runs and sessions within baseline	6(S-1)[b]

[a] Treatments = Baseline, radiation, and recovery

[b] 6 for Phase I data, but 3 for Phase II data

[c] S = Number of sessions (different for PEP, PEP + MART, MART)

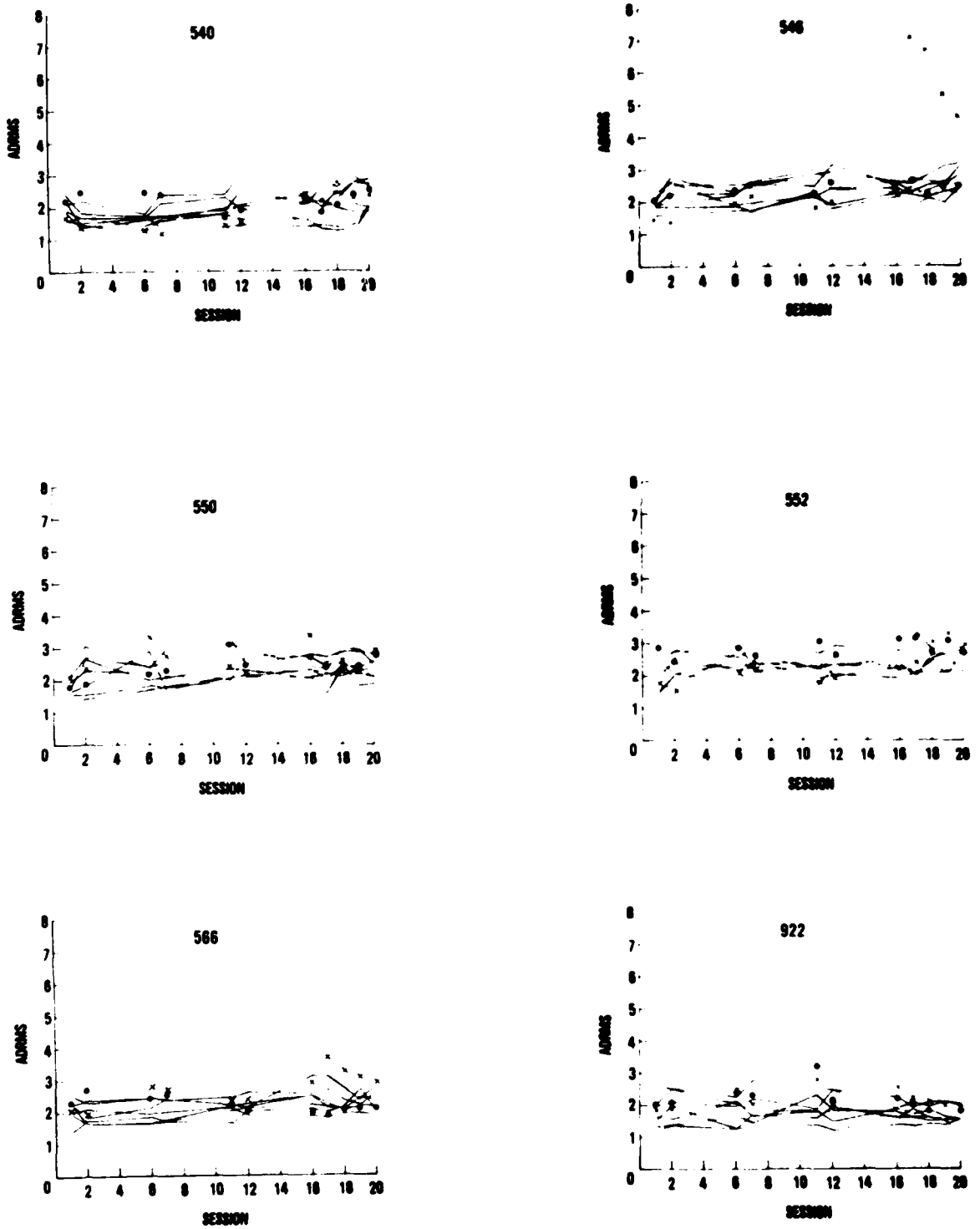


Figure 6. Adjusted RMS error in operating the PEP. (In Figs. 6-8, solid lines = scores made during each baseline; x's = scores on radiation days; ●'s = scores from identical testing the day after radiation.)

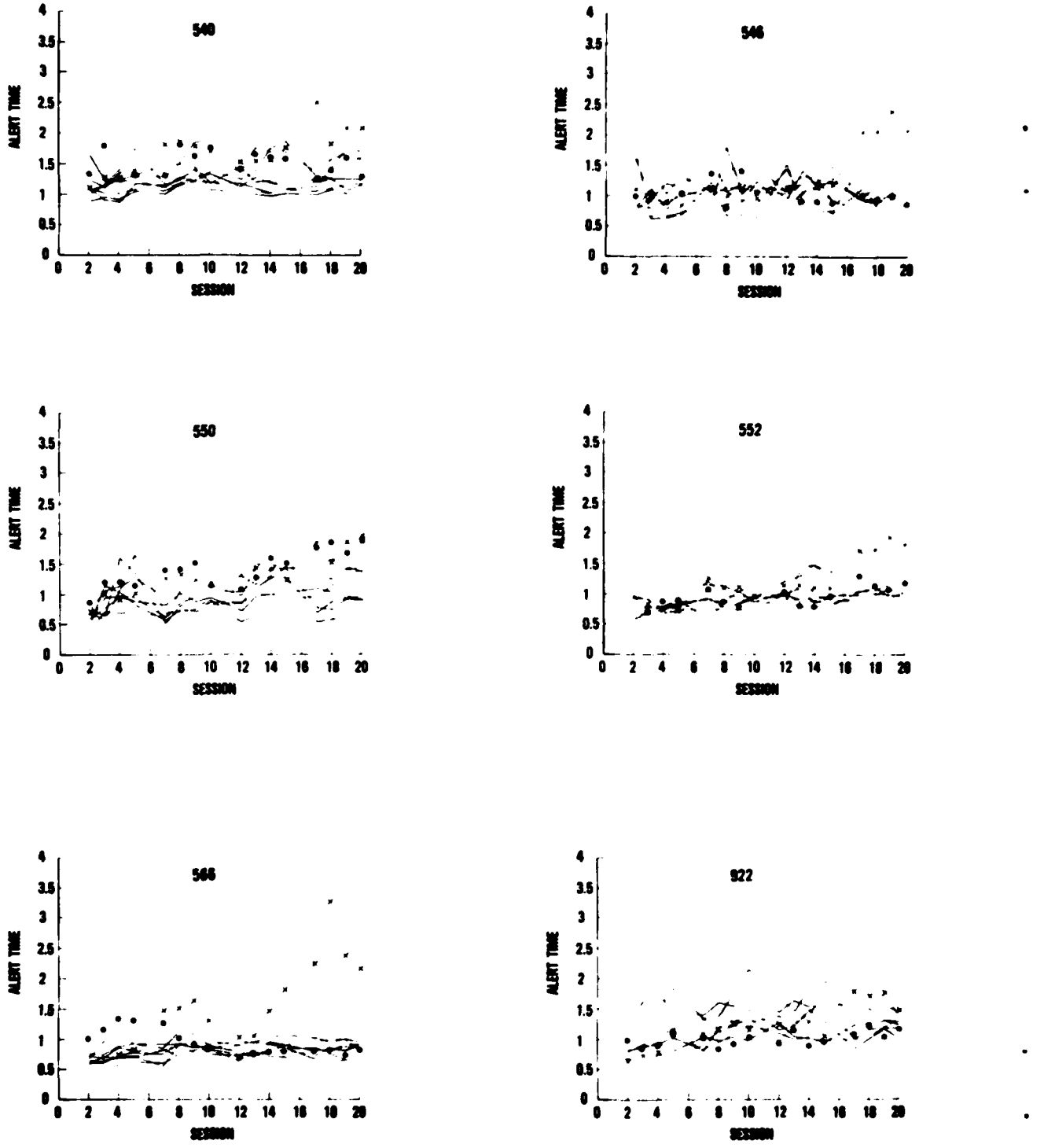


Figure 7. Phase I. Time in seconds required to extinguish alert light.

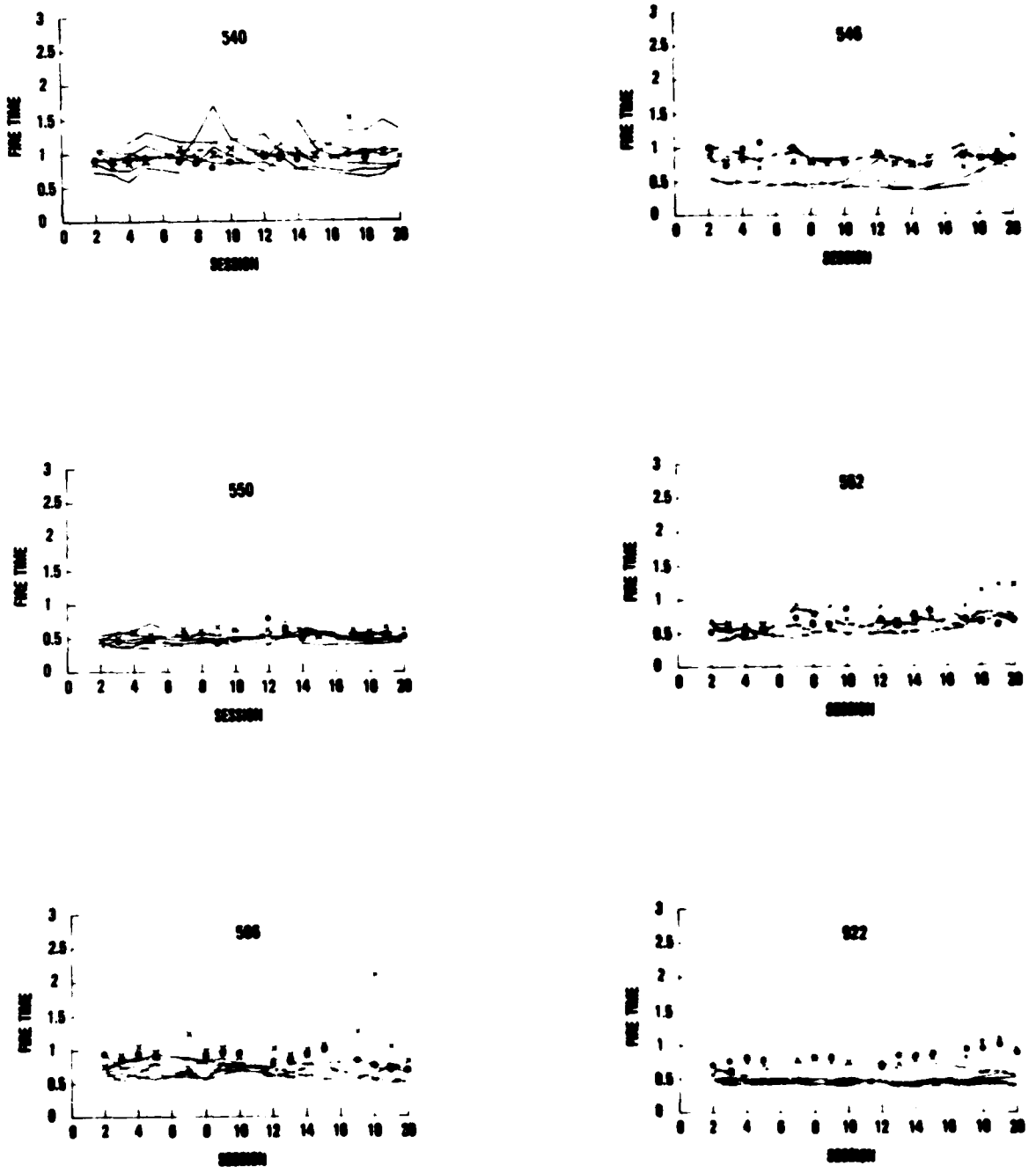


Figure 8. Phase I. Time in seconds required to extinguish fire light.

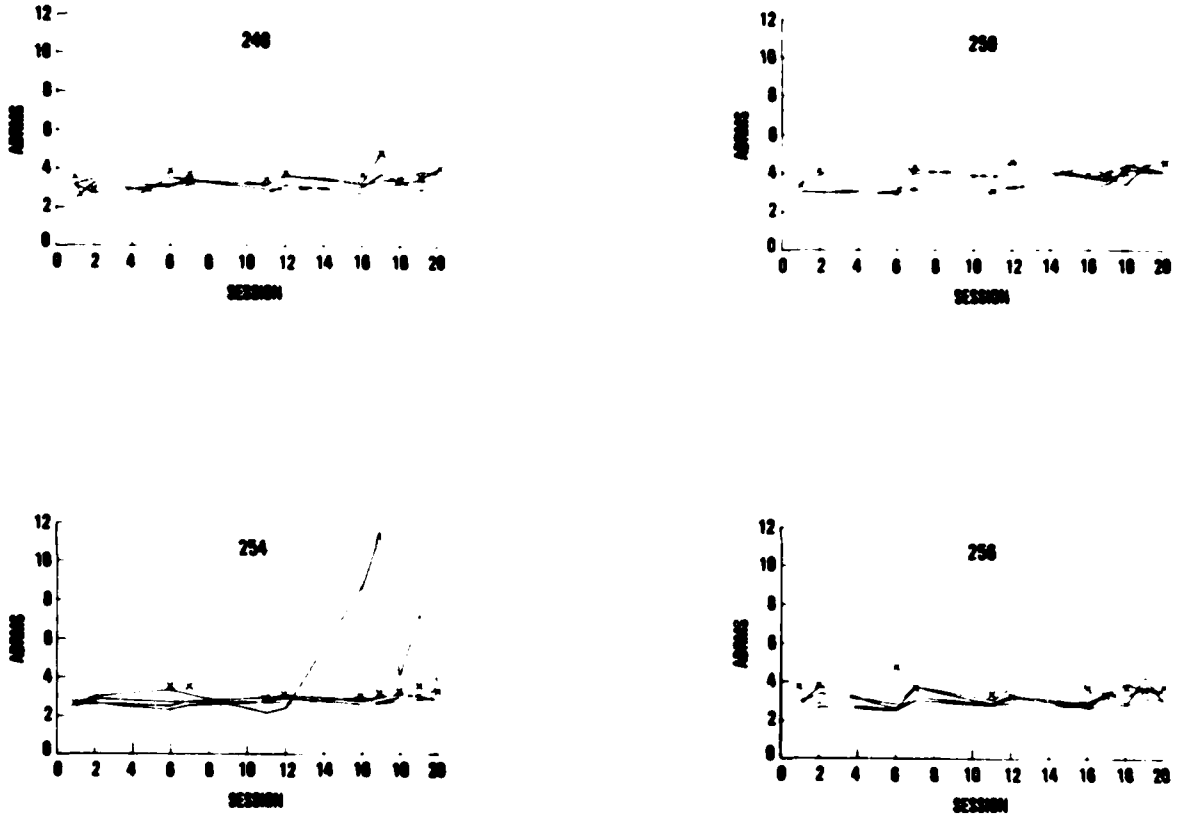


Figure 9. Phase II. Adjusted RMS error in operating the PEP. (In Figs. 9-11, solid lines = scores made during each baseline, and x's = scores on radiation days.)

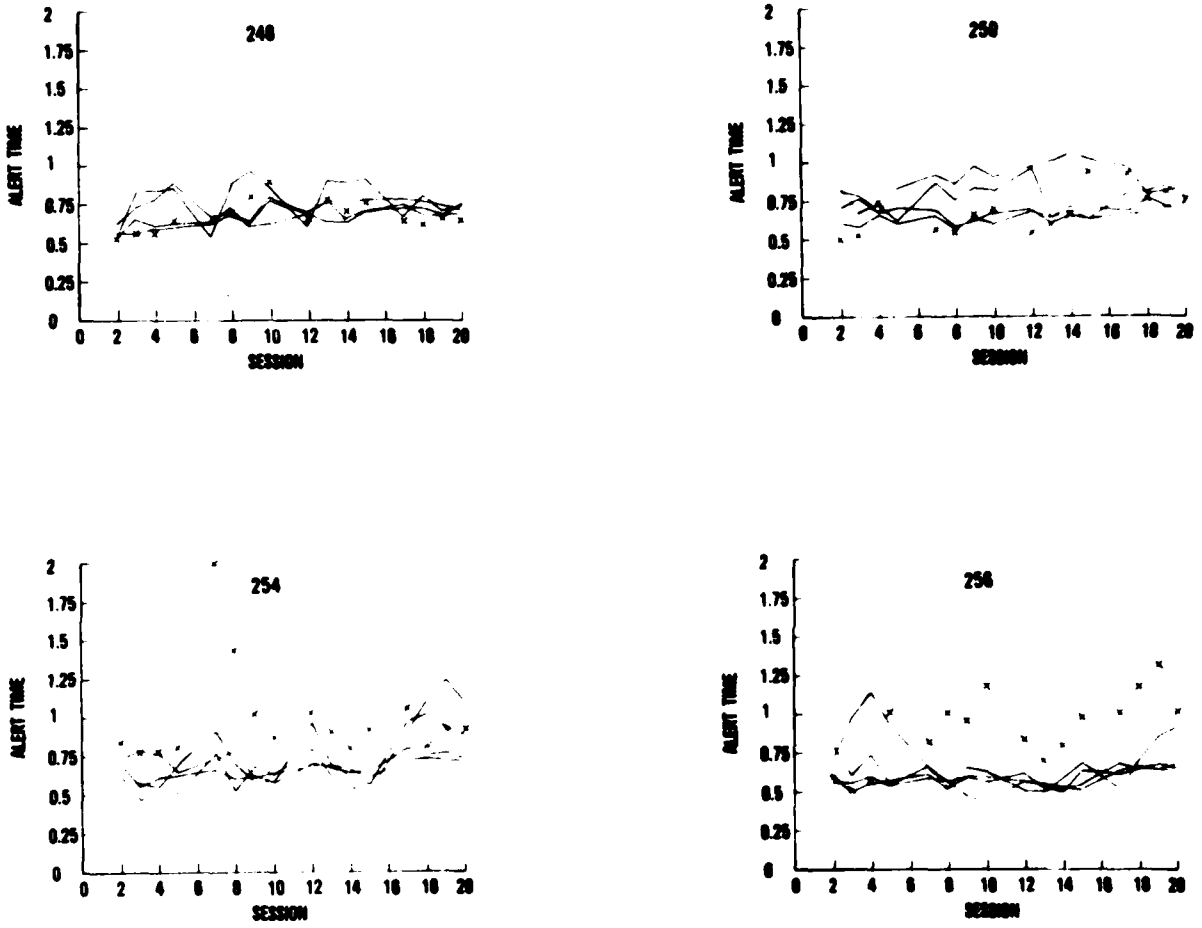


Figure 10. Phase II. Time in seconds required to extinguish alert light.

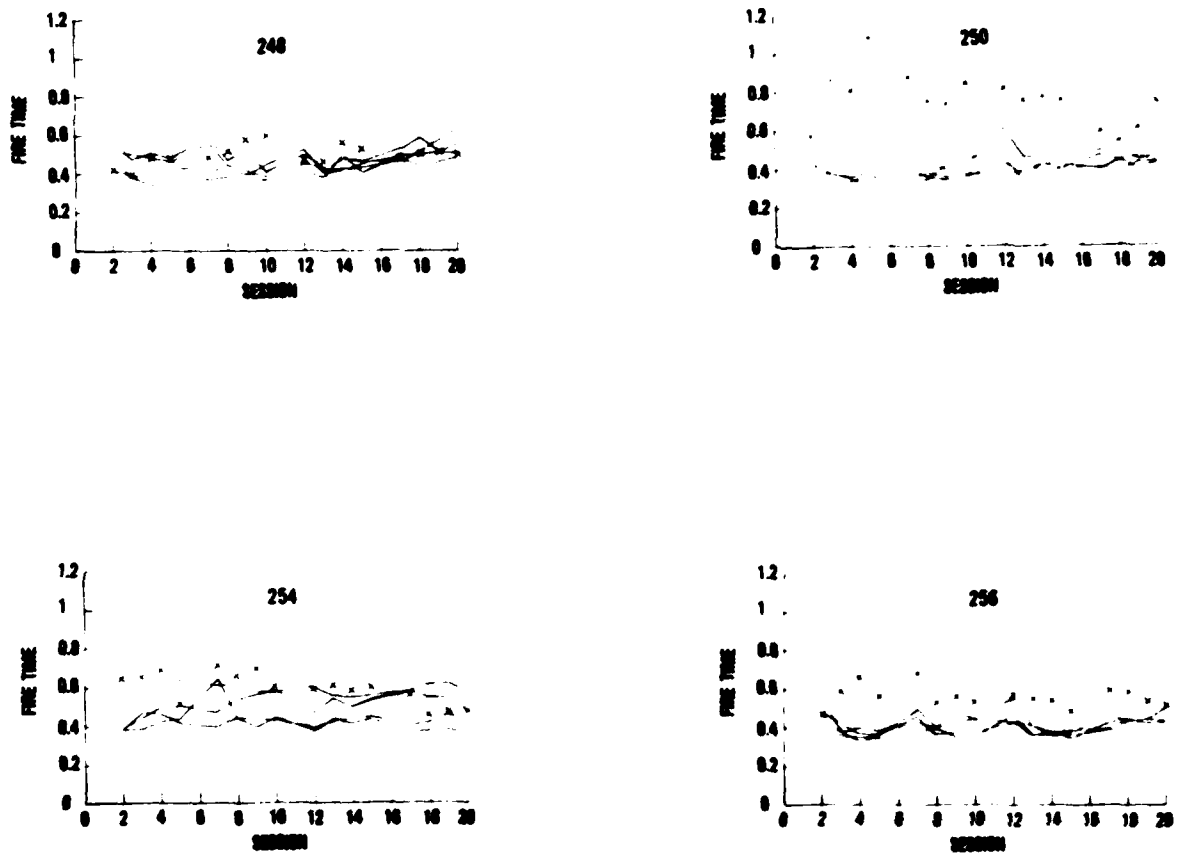


Figure 11. Phase II. Time in seconds required to extinguish fire light.

See Table 2 for the probability levels associated with these two sources (treatment and treatment-by-session) of variation on each analysis.

TABLE 2. PROBABILITY LEVELS FOR TREATMENT AND TREATMENT-BY-SESSION INTERACTION FOR EACH ANOVA ON PHASE I

Measurement:		Adjusted root mean square		Reaction time (alert)		Reaction time (fire)	
Set	Subject	Treatment	Treatment-session interaction	Treatment	Treatment-session interaction	Treatment	Treatment-session interaction
PEP	540	x	x	x	x	x	x
only	546	x	x	x	x	x	.001
or	550	x	x	x	x	x	x
MART	552	x	x	x	x	x	x
only	566	x	.05	.05	.001	.05	x
	922	x	.05	x	x	.05	.05
PEP	540	x	x	.05	.001	x	.01
&	546	.05	.001	x	.001	x	x
MART	550	x	x	.05	x	.05	.001
	552	x	x	x	x	x	x
	566	x	.001	.001	.001	.01	.001
	922	x	x	x	.01	.01	.001

x = $p > .05$
.05 = $p < .05$
.01 = $p < .01$
.001 = $p < .001$

Additional baseline-vs-radiation and baseline-vs-recovery comparisons were made, and the probability level for each session for each subject for the baseline-vs-radiation exposure for the PEP is presented in Table 3. This table reflects statistically significant performance decrements for this dependent variable for two subjects (546 and 566) after the 1200-rad (12.0 Gy) exposure administered at session 16. Only one subject (550) exhibited a performance decrement ($p < .05$) prior to the large radiation exposure at session 16. The probability values for the baseline-vs-recovery ADRMS are presented in Table 4. This table reflects the fact that four Ss exhibited performance decrements ($p < .05$) for at least one session. Probability values for the alert reaction time for baseline vs radiation exposure for Phase I (Table 5) and baseline vs recovery (Table 6) reflect more performance decrement than

TABLE 3. PROBABILITY VALUES FOR ADJUSTED-RMS ERROR: PHASE I - BASELINE VS RADIATION

Session	Subjects					
	540	546	550	552	566	922
1 (PEP only)	x	x	x	x	x	x
2	x	x	x	x	x	x
6 (PEP only)	x	x	.05	x	x	x
7	x	x	x	x	x	x
11 (PEP only)	x	x	x	x	x	x
12	x	x	x	x	x	x
16 (PEP only)	x	x	x	x	x	x
17	x	.001	x	x	.001	x
18	x	.001	x	x	.01	x
19	x	.001	x	x	.05	x
20	x	.001	x	x	x	x

TABLE 4. PROBABILITY VALUES FOR ADJUSTED-RMS ERROR: PHASE I - BASELINE VS RECOVERY

Session	Subjects					
	540	546	550	552	566	922
1 (PEP only)	x	x	x	x	x	x
2	x	x	x	x	.05	x
6 (PEP only)	.05	x	x	x	x	x
7	x	x	x	x	x	x
11 (PEP only)	x	x	x	.05	x	.05
12	x	x	x	x	x	x
16 (PEP only)	x	x	x	.05	x	x
17	x	x	x	x	x	x
18	x	x	x	x	x	x
19	x	x	x	x	x	x
20	x	x	x	x	x	x

x = p >.05
.05 = p <.05
.01 = p <.01
.001 = p <.001

observed on the ADRMS. Four of the six Ss exhibited statistically significant performance decrements after the session-16 exposure (1200 rad, 12.0 Gy). Two of these Ss (540 and 566) exhibited decrements beginning at session 7 (after the earlier 240-rad exposure). Three Ss exhibited performance decrements in at least one session of the recovery test. Note that two Ss (540 and 566) exhibited statistically slower reaction times early in the recovery test (sessions 2 and 3) but exhibited no statistically significant differences at the end of the test (e.g., sessions 19-20). Probability values for the reaction-time (fire) dependent variable for baseline vs radiation are presented in Table 7. Five of the six Ss exhibited some statistically significant decrement, but subject 922 exhibited the most sustained performance decrement (14 of 16 sessions). Additionally, subject number 922 appeared to continue to perform slowly on this task on the recovery test (see Table 8).

Data were collected and analyzed in a similar manner for the low-dose group (Phase II), although recovery could not be compared to baseline. See Table 9 for associated probability levels. The resultant probability values of the tests of baseline vs radiation are presented as Tables 10-12. Only one of the four subjects (256) demonstrated performance decrement in operating the PEP. For the reaction tasks, as in Phase I testing, in many sessions the performance was statistically poorer than baseline performance. In Table 11, the reaction times (alert) are depicted. Although all four subjects started out well, two of them (254 and 256) began lengthy periods of poor performance by sessions 7 and 5 respectively. The other subject (248) demonstrating any degree of decrement only had one session of significantly poor performance. Then, on the reaction time (fire), Table 12, even more total sessions demonstrated significant decrements in performance when each monkey's day of radiation exposure was compared to his own baseline. Subject 256 had poorer performance for most sessions, while subject 248 had only two sessions with notably poor performance. Subject 250 had decrement in all but one session on this test, even though he had good performance on the other two tests. In contrast, subject 254 had no significant variability on this test but poor performance on the alert test. In comparing the MART pre- and postirradiation performance, the approximate average difference in reaction (determined visually from Figs. 10 and 11) is a slowing, after radiation, by 0.5 second on the alert task and 0.2 second on the fire task.

Visual Observations

As noted earlier, the subjects were closely observed during the baselines and exposure and postexposure test days via closed-circuit television. Also, the exposure and postexposure tests were video taped for observation to identify changes in behavior caused by the radiation exposure and to gain insight into the quantitative changes in performance detected in the comparative analyses previously discussed.

Symptoms resulting from exposure of humans to radiation include headache, nausea, emesis, malaise, marked weakness, anorexia, and in some cases, temporary incapacitation or inability to maintain meaningful performance (6, 14). Since animal subjects cannot verbally communicate symptoms, and automated procedures to detect these kinds of effects are suspect, visual observations

TABLE 5. PROBABILITY VALUES FOR REACTION TIME (ALERT): PHASE I - BASELINE VS RADIATION

Session		Subjects 540	546	550	552	566	922
2		x	x	x	x	x	x
3	(MART only)	x	x	x	x	x	x
4	(MART only)	x	x	x	x	x	x
5	(MART Only)	x	x	x	x	x	x
7		.05	x	x	x	.001	x
8	(MART only)	.05	x	x	x	.001	x
9	(MART only)	x	x	x	x	.001	x
10	(MART only)	x	x	x	x	.01	x
12		x	x	x	x	x	x
13	(MART only)	x	x	x	x	x	x
14	(MART only)	x	x	x	x	.001	x
15	(MART only)	x	x	x	x	.001	x
17		.001	.01	.01	x	.001	x
18		.05	.01	x	x	.001	x
19		.01	.01	.05	x	.001	x
20		.01	.05	.01	x	.001	x

TABLE 6. PROBABILITY VALUES FOR REACTION TIME (ALERT): PHASE I - BASELINE VS RECOVERY

Session		Subjects 540	546	550	552	566	922
2		x	x	x	x	.05	x
3	(MART only)	.05	x	x	x	.01	x
4	(MART only)	x	x	x	x	.001	x
5	(MART only)	x	x	x	x	.001	x
7		x	x	.05	x	.01	x
8	(MART only)	x	x	x	x	x	x
9	(MART only)	x	x	.05	x	x	x
10	(MART only)	x	x	x	x	x	x
12		x	x	x	x	x	x
13	(MART only)	x	x	x	x	x	x
14	(MART only)	x	x	x	x	x	x
15	(MART only)	x	x	x	x	x	x
17		x	x	.05	x	x	x
18		x	x	.05	x	x	x
19		x	x	x	x	x	x
20		x	x	.05	x	x	x

x = p >.05
.05 = p <.05
.01 = p <.01
.001 = p <.001

TABLE 7. PROBABILITY VALUES FOR REACTION TIME (FIRE): PHASE I - BASELINE VS RADIATION

Session		Subjects 540	546	550	552	566	922
2		x	x	x	x	x	x
3	(MART only)	x	x	x	x	x	x
4	(MART only)	x	x	x	x	.05	.05
5	(MART only)	x	x	x	x	x	.05
7		x	x	.01	x	.001	.05
8	(MART only)	x	x	x	x	.05	.01
9	(MART only)	x	x	.05	.05	.05	.05
10	(MART only)	x	x	x	x	x	.05
12		x	x	.05	x	.05	.05
13	(MART only)	x	x	x	x	x	.05
14	(MART only)	x	x	x	x	.05	.05
15	(MART only)	x	x	x	x	.01	.05
17		.05	x	.05	x	.001	.01
18		x	x	.05	x	.001	.001
19		x	x	.01	.05	.01	.001
20		x	x	.05	.01	x	.001

TABLE 8. PROBABILITY VALUES FOR REACTION TIME (FIRE): PHASE I - BASELINE VS RECOVERY

Session		Subjects 540	546	550	552	566	922
2		x	x	x	x	.05	x
3	(MART only)	x	x	x	x	x	.05
4	(MART only)	x	x	x	x	x	.05
5	(MART only)	x	x	x	x	x	.05
7		x	x	x	x	x	x
8	(MART only)	x	x	x	x	x	.01
9	(MART only)	x	x	x	x	x	.01
10	(MART only)	x	x	x	.05	x	.05
12		x	x	.001	x	x	x
13	(MART only)	x	x	x	x	x	.01
14	(MART only)	x	x	x	x	x	.01
15	(MART only)	x	x	x	x	.05	.01
17		x	x	.05	x	x	.001
18		x	x	x	x	x	.001
19		x	x	x	x	x	.001
20		x	x	x	x	x	.01

x = $p > .05$
.05 = $p < .05$
.01 = $p < .01$
.001 = $p < .001$

TABLE 9. PROBABILITY LEVELS FOR TREATMENT AND TREATMENT-BY-SESSION INTERACTION FOR EACH ANOVA ON PHASE II

Measurement:		Adjusted root mean square		Reaction time (alert)		Reaction time (fire)	
Set	Subject	Treatment	Treatment-session interaction	Treatment	Treatment-session interaction	Treatment	Treatment-session interaction
PEP only or MART only	248	x	x	x	x	x	.05
	250	x	x	x	x	.001	.001
	254	x	x	.01	.001	x	.01
	256	.01	.001	x	.01	.01	.05
PEP & MART	248	x	x	x	x	x	x
	250	x	x	x	.001	.01	.001
	254	x	x	x	.001	x	x
	256	x	x	.01	.01	.05	x

TABLE 10. PROBABILITY VALUES FOR ADJUSTED-RMS ERROR: PHASE II - BASELINE VS RADIATION

Session	Subject 248	250	254	256
1 (PEP only)	x	x	x	.001
2	x	x	x	x
6 (PEP only)	x	x	x	.001
7	x	x	x	x
11 (PEP only)	x	x	x	.05
12	x	x	x	x
16 (PEP only)	x	x	x	.01
17	x	x	x	x
18	x	x	x	x
19	x	x	x	x
20	x	x	x	x

x = $p > .05$
.05 = $p < .05$
.01 = $p < .01$
.001 = $p < .001$

TABLE 11. PROBABILITY VALUES FOR REACTION TIME (ALERT): PHASE II - BASELINE VS RADIATION

Session	Subject 248	250	254	256
2	x	x	x	x
3 (MART only)	x	x	x	x
4 (MART only)	x	x	x	x
5 (MART only)	x	x	x	.05
7	x	x	.001	.05
8 (MART only)	x	x	.001	.05
9 (MART only)	x	x	.001	.05
10 (MART only)	x	x	.05	.01
12	x	x	x	.01
13 (MART only)	x	x	.05	x
14 (MART only)	x	x	x	x
15 (MART only)	x	x	.01	.05
17	x	x	x	.001
18	.05	x	x	.001
19	x	x	x	.001
20	x	x	x	.01

TABLE 12. PROBABILITY VALUES FOR REACTION TIME (FIRE): PHASE II - BASELINE VS RADIATION

Session	Subject 248	250	254	256
2	x	.05	x	x
3 (MART only)	x	.001	x	.001
4 (MART only)	x	.001	x	.001
5 (MART only)	x	.001	x	.001
7	x	.001	x	.001
8 (MART only)	x	.001	x	.001
9 (MART only)	.05	.001	x	.001
10 (MART only)	.01	.001	x	.001
12	x	.001	x	x
13 (MART only)	x	.001	x	.001
14 (MART only)	x	.001	x	.001
15 (MART only)	x	.001	x	.01
17	x	.05	x	.01
18	x	x	x	.01
19	x	.05	x	.05
20	x	.01	x	x

x = $p > .05$
.05 = $p < .05$
.01 = $p < .01$
.001 = $p < .001$

are required. The signs most conducive to reliable reporting by visual observation are productive emesis and incapacitation. In such cases, the sign leaves little doubt. However, other signs are more subtle, and the interpretation of visual observations more subjective.

Retching is rather difficult to quantify; and with animal subjects, reporting its assumed precurser, nausea, is even more subjective. We defined retching as movements that appeared to be involuntary contractions of the abdominal muscles, with or without open-mouth (gagging) responses. Generally, one or more spells of mouthing (heavy chewing-like motions that suggest nausea) preceded the retching responses. Figure 12 depicts the retching and productive emesis observed during the exposure day of Phase I. Note that two of the subjects experienced significant retching responses and mild productive emesis after exposure to the relatively low radiation doses delivered in the first 2 hours of the experimental day. Also, five of the six subjects experienced profuse productive emesis after the large dose administered at the start of session 16. Only one subject, 550, did not experience productive emesis at any time.

No emesis or indications of nausea were observed in the Phase I subjects after session 20 or during the next day. Nor were any of the four subjects of Phase II afflicted with signs characteristic of nausea or emesis during or after the entire 10-hour exposure workday.

All six subjects in Phase I displayed intermittent spells of listlessness and lethargy during the last 5 hours of the 10-hour experiment. This visual observation correlates well with observations made by others for human patients and accident victims. However, two subjects appeared extremely lethargic and disoriented after the large radiation dose. In fact, subject 566 exhibited behavioral incapacitation, maintaining only marginal control of the PEP and almost totally ignoring the MART cue lights.

Anorexia was also difficult to evaluate. An early indication of anorexia during the exposure day of the Phase I study was the refusal of three of the six subjects to accept the fruit provided them after session 20. Additionally, all subjects refused to eat their normal ration of biscuits at the completion of the 10-hour exposure day. In fact, except for minor exceptions, all subjects continued to refuse biscuits; however, they did accept and consume fruit (apples and oranges) the day after exposures. This selectivity could be due to their preference for fruit or to the fact that the fruit contained moisture and was easier to consume. Phase I animals were euthanized the day after their last postirradiation test. Animals used in Phase II were euthanized the day after their exposure, so no data on performance or food consumption were obtained postirradiation.

DISCUSSION

Results of the Phase I experiment reflect the difficulty these subjects experienced in completing a 10-hour mission simulation with additional severe radiation stress. The entire experimental treatment day (10 hours of PEP/MART operation and radiation exposures) was video taped for more detailed study. In these visual observations, behavior suggestive of nausea, fatigue, and

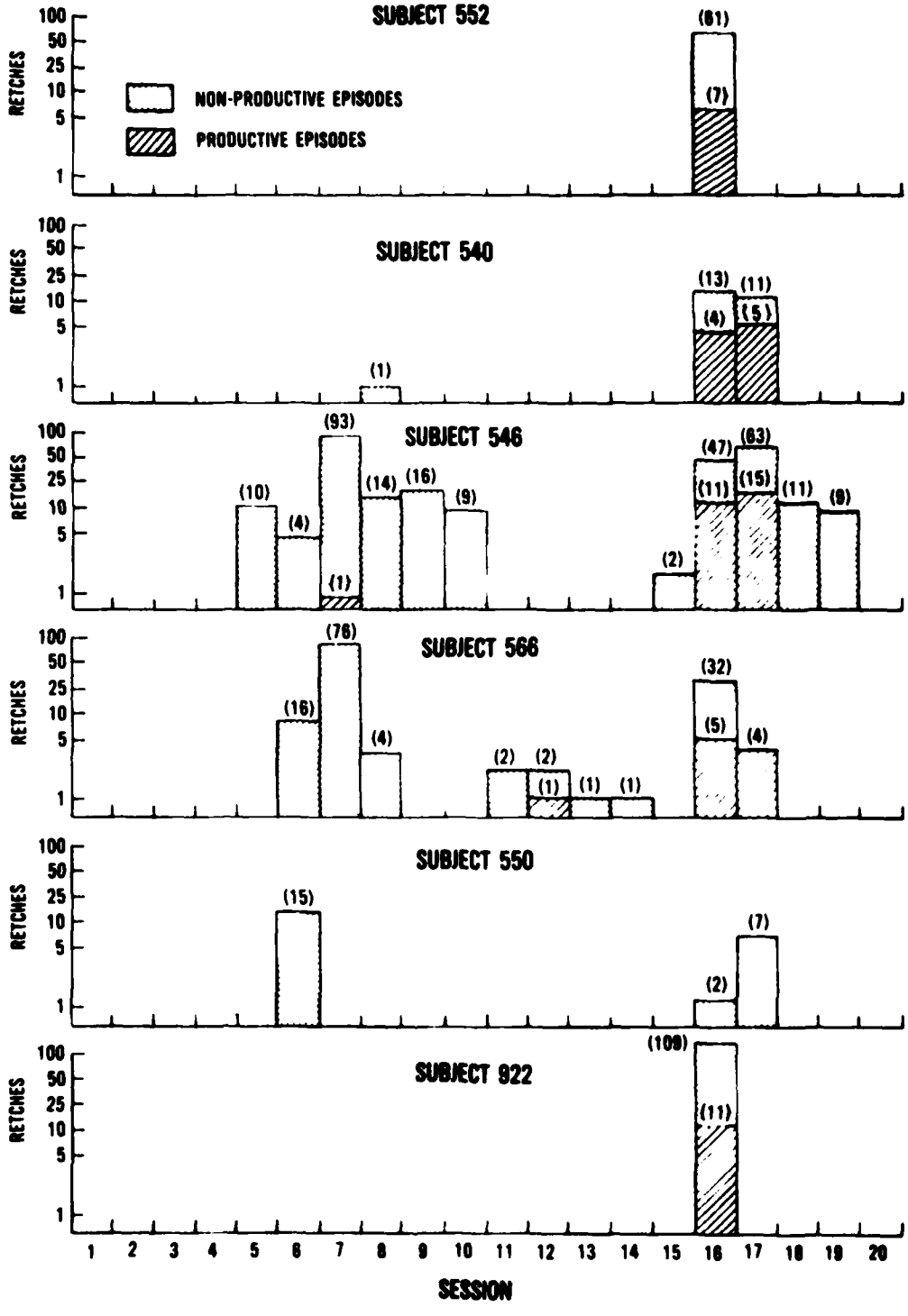


Figure 12. Phase I. Retching and emesis as a result of radiation exposure.

discomfort, as well as the more obvious responses of retching and productive emesis, were noted. Such observations provide additional insight into the subjects' general condition, thereby supplementing the more quantitative performance data.

Visual observation and statistical evaluation of data mutually support the fact that radiation effects were more readily observed in MART performance than in PEP. PEP control for these highly proficient animals seemed to be almost reflexive. The periodic effort to concentrate required by response to MART cues appeared to tax the subjects more heavily.

The major measures of MART performance are times required to respond to alert and fire lights and the accuracies of such responses. MART response times were the most sensitive of the measures taken, although perusal of Tables 5 and 7 demonstrates that even decrements noted on this variable are relatively mild for at least three (540, 546, 552) of the subjects prior to the large radiation dose. The overall effect can only be hypothesized, however, when operational tasks which are very time critical are adversely affected by exposure to ionizing radiation of the intensity and duration utilized throughout this experiment.

Based on evaluations during the experimental day and of video tapes, a subjective estimate of performance capability on mission impact was made (Fig. 13). When comparing this with the summary of emetic behavior (Fig. 12), we observe a high degree of relationship in two subjects (546 and 550). The relationship of emetic activity and performance decrement is moderate in subjects 540 and 566 and is minimal in the other two.

Based on the statistics of performance capability, severe decrement occurred in three subjects during session 16. This is the same session in which they had productive emesis. The productive emesis abated within 40 minutes after the large dose of radiation was administered, but the performance decrement was severe throughout a 2-hour period beginning with session 16. Following their "emetic phase" associated with the high-radiation exposure, most subjects exhibited an extreme degree of lethargy, becoming almost catatonic in appearance. They slumped in their couches, performed erratically, and several exhibited exaggerated posturing.

Near the end of session 20, all subjects (even those most affected) had recovered to the extent that performance was improved and the subjects appeared more alert to environmental cues. By the next day, all subjects were performing quite well, with only relatively minor observable changes from their preexposure behavior.

Another consideration pertaining to the emetic response of these subjects and its apparent relationship with performance decrement is that monkeys appear more tolerant to radiation effects than man. In fact, rhesus monkeys' LD_{50} is twice that of man, and the ED_{50} (radiation dose required for emesis in 50% of subjects) is 2.5 times that of man (9). The inference is that these effects would occur in humans at doses of 700 rad (7.0 Gy) or less. On the other hand, monkeys seem to respond to radiation more rapidly than humans (9), so possibly the irradiated human would have a somewhat extended useful working period.

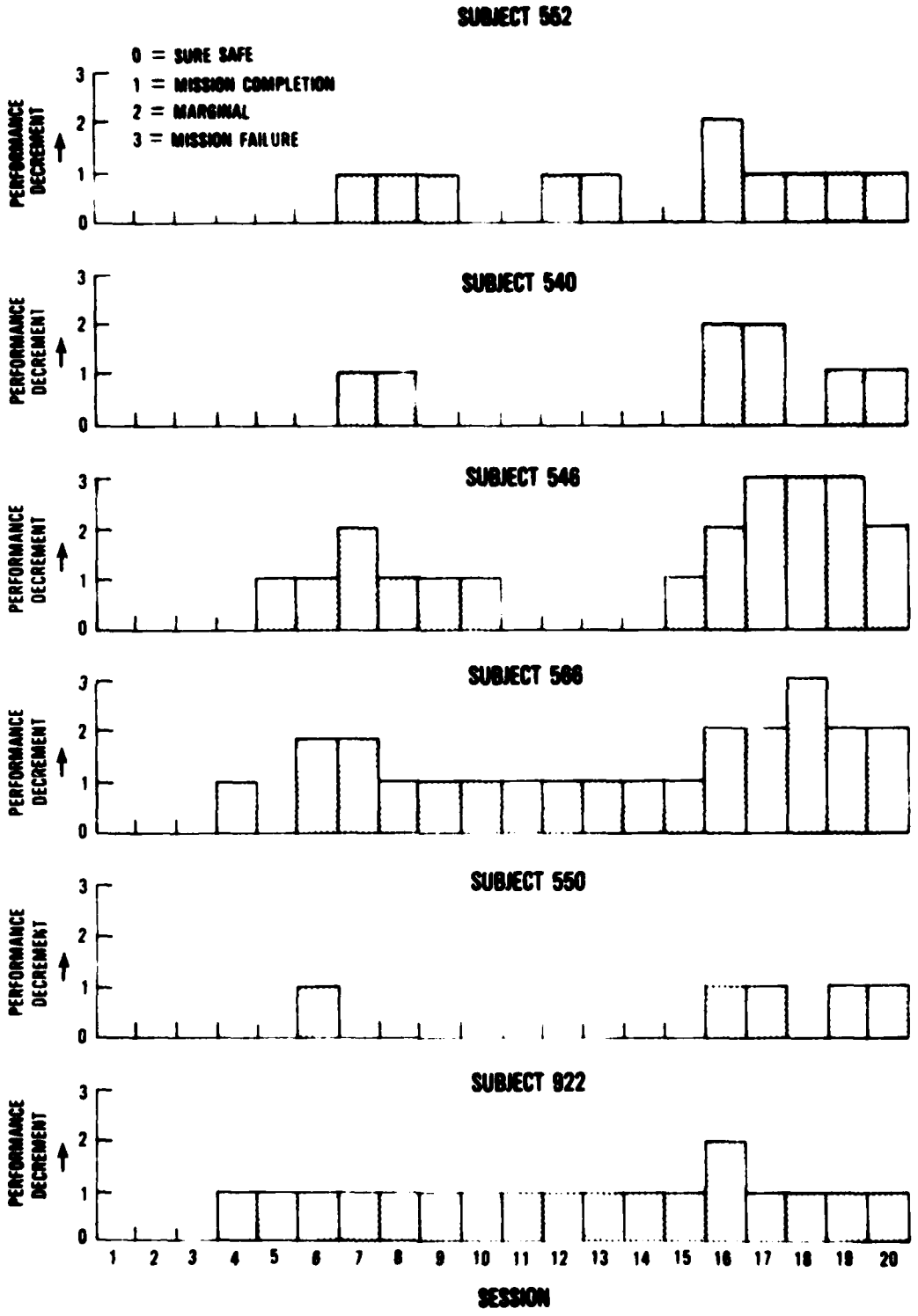


Figure 13. Phase I. Subjective summary of mission impacts.

CONCLUSIONS

In summary, two (546 and 566) of the six subjects in Phase I of this experiment were severely affected by the radiation delivered, while a third (540) demonstrated periods of performance described as marginal at best. As the psychological debilitation suffered by man (who is aware of his environment, as the monkey is not) may well be significant in itself, satisfactory mission completion in such a high-dose environment would not seem probable for all crewmembers.

The Phase II (360 rad, 3.6 Gy, profile) experiment yielded less drastic results. None of the four subjects experienced incapacitation, and none totally lost control of the PEP. However, all four subjects exhibited at least one session in which performance was significantly poorer than baseline performance would predict. Note from the graphs (see Figs. 10 and 11) that reaction time was significantly slower: a difference of approximately 0.5 second for the alert task and 0.2 second for the fire task. The operational significance of reactions that are fractions of a second slower depends upon the operational task. Although these subjects were not incapacitated, they were not working as well as baseline predictions. Thus we cannot conclude that this low-dose scenario is a no-effect level of radiation exposure, but mission success is highly probable.

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APPENDIX A

SIMULATION OF AIRCREW RADIATION PROFILE ON USAFSAM AECL CO-60 SOURCE

The required radiation exposure profile was to consist of: (1) an initial dose of 100 rad (1.0 Gy) delivered in 2 minutes at the beginning of the experimental day to simulate the ionizing dose received during base escape; (2) a 35-rad (0.35 Gy) dose delivered in 2 minutes at 1 hour into the day; (3) a 105-rad (1.05 Gy) dose delivered in 15 minutes at 2 hours into the day; (4) a pulsed dose of 1200 rad (12.0 Gy) or 120 rad (1.2 Gy) delivered at 7.5 hours into the day to simulate exposure to a near-miss detonation of a defensive missile. The 35- and 105-rad (0.35 and 1.05 Gy) doses simulated exposure to radioactive cloud penetration during the first hour after takeoff. The total experimental operating time was 10 hours. An accumulated total dose (midline) of 1440 rad (14.4 Gy) or 360 rad (3.6 Gy) was required in Phases I and II respectively. The USAFSAM/RZ AECL Co-60 facility was used for this study because of the high-dose rates available for simulating the required exposure profile.

Dosimetry Procedures

The initial stage involved determining the free-in-air exposure rates in roentgens/unit-time necessary to deliver the required midline dose rates in rad/unit-time. Using a rad-to-roentgen conversion factor of 0.95 for tissue and an approximate attenuation factor of 0.90 based on clinical depth-dose data, we obtained a factor of approximately 0.86 to convert exposure dose to midline absorbed dose. With this as a starting point, we made corroborative measurements using an Alderson plastic tissue-equivalent primate phantom containing LiF thermoluminescent dosimeters. Measurements made at varying distances, corresponding to the approximate exposure distances required for the animal exposure, gave a mean-midline-dose conversion factor of 0.88.

Using this empirically determined factor, we computed exposure rates and distances for the required midline dose rates. These results are listed in Table A1. The distances listed in Phase I are for the source calibrations of 1 Nov 1976. For the animals subsequently exposed in December 1976, additional time was added to the exposure time to compensate for source decay. Field uniformity considerations imposed a minimum midline distance of 105 cm for the highest possible dose rate (96 rad/min, 0.96 Gy/min, for Phase I and 144.9 rad/min, 1.449 Gy/min, for Phase II).

We then exposed the Alderson primate phantoms containing LiF dosimeters, in the same manner as the animals were exposed in Phase I; that is, in the PEP platforms facing the beam. Two independent measurements gave average midline doses of 1451 and 1449 rad (14.51 and 14.49 Gy), respectively, for the upper two-thirds of the torso, in excellent agreement with the programmed value. The dose to the lower one-third of the torso was approximately 70% of the programmed value due to shielding effects by the PEP chair.

TABLE A1. SUMMARY OF EXPOSURE CONFIGURATIONS

Phase I - 1440-Rad (14.4 Gy) Total Dose

Position	Programmed midline dose rate (rad/min)	Free-field exposure[a] rate (R/min)	Midline distance[b] (cm)	Exposure time (min)	Midline dose (rad)
I	50 (0.5 Gy)	56.8	145.6	2.0	100 (1.0 Gy)
II	17.5 (0.175 Gy)	19.9	246.0	2.0	35 (0.35 Gy)
III	7.0 (0.07 Gy)	8.0	388.0	15.0	105 (1.05 Gy)
IV	96.1 (0.961 Gy)	109.2	105.0	12.5	1200 (12.0 Gy)
				Total dose	1440 rad (14.4 Gy)

Phase II - 360-Rad (3.6 Gy) Total Dose

I	50 (0.5 Gy)	56.8	167.7[c]	2.0	100 (1.0 Gy)
II	17.5 (0.175 Gy)	19.9	283.3	2.0	35 (0.35 Gy)
III	7.0 (0.07 Gy)	8.0	477.6	15.0	105 (1.05 Gy)
IV	127.5 (1.275 Gy)	144.9	105.0	0.94	120 (1.2 Gy)
				Total dose	360 rad (3.6 Gy)

[a] Based on empirically measured midline to free field dose ratio of 0.88.

[b] Computed from November 1976 Co-60 source calibration.

[c] Computed based on April 1979 source activity.

Thermoluminescent and ionization monitor dosimeters were also exposed simultaneously with the phantoms to obtain correlation factors for monitoring the animal exposures. The ionization monitor used was a Victoreen Model 55-10HA probe attached to a Victoreen Model 555 remote reader. The ionization monitor was mounted on the PEP platform, behind the animal, on a line of sight with the source. The TL monitor dosimeter was positioned on the front of the PEP platform. Monitor doses obtained during the phantom exposures under Phase I conditions were 1043 and 2743 rad (10.43 and 27.43 Gy), respectively, for the two systems.

Type-700 LiF thermoluminescent dosimeter powder encapsulated in polyethylene tubing was used in the phantom measurements. The dose response of this material was determined by comparing its response to known Co-60 doses delivered in the AECL Co-60 source. This source has been calibrated with NBS-calibrated 3-terminal, guarded configuration ionization chambers and Victoreen Condenser Chamber. The LiF powder was read-out on a Harshaw Model 2000 thermoluminescence dosimeter reader. Approximately five readings were obtained from each phantom dosimeter site per exposure.

Animal Irradiations

The animals were exposed whole body, anterior-posterior, while seated on aluminum chairs in the primate equilibrium platform. (Fig. 5 illustrates the exposure configurations used on the animal irradiations.) The Ss were initially exposed to 100 rad (1.0 Gy) at 50 rad/min (midline) at source-to-midline distances of 145.6 and 167.7 cm in Phases I and II respectively. They were then moved back to 246.0 cm (Phase I) or 283.3 cm (Phase II) and exposed at 1 hour into the experimental day for 2 minutes at 17.5 rad/min (0.175 Gy/min) (midline). At 2 hours into the experimental day, the animals were moved back to 388.0 cm (Phase I) or 477.6 cm (Phase II) and irradiated for 15 minutes at 7.0 rad/min (0.07 Gy/min). Finally, at 7.5 hours into the experimental day, the animals were positioned at 105 cm source-to-midline distance and exposed for 12.5 minutes at 96 rad (0.96 Gy) per minute in Phase I and 0.83 minute at 144.9 rad (1.449 Gy) per minute in Phase II. For Phase I animals exposed in December, the exposure times were increased by 1.1% to compensate for source decay. (Fig. 3 illustrates the accumulated dose vs experimental time.) A summary of the Phase I animal exposures is listed in Table A2. Included in this table are the results of the monitor dosimeters. These data indicate that the animals were exposed to within 95% of the programmed doses. No monitor dosimeters were exposed with the Phase II animals. Dosimetry measurements in Alderson primate phantoms, performed prior to the Phase II exposure series to check for possible effects of the new source, yielded the same midline:free-field dose ratio (0.88) as obtained in Phase I.

Summary

An ionizing radiation environment simulating a hypothetical strategic-aircraft aircrew exposure profile was developed on the USAFSAM Co-60 facility. Different source-to-animal midline distances were used to attain the required dose rates. In Phase I, six trained primates were exposed to this environment while performing hypothetical aircrew tasks of loading and scheduling. All Ss

TABLE A2. SUMMARY OF PRIMATE EXPOSURE

Animal No.	Date of exposure	Radocon monitor[a]	TLD monitor[b]
922	15 Nov 76	1039 (100)	2595 (95)
550	17 Nov 76	1062 (102)	2730 (100)
566	22 Nov 76	1019 (98)	2650 (97)
546	29 Nov 76	1005 (96)	2715 (99)
540	1 Dec 76	1045 (100)	2758 (101)
552	8 Dec 76	1043 (100)	2752 (100)

[a]Predicted value from phantom measurements: 1043 rad

[b]Predicted value from phantom measurements: 2743 rad

Note: Values in parentheses are percentages (ratios of monitor doses to programmed monitor responses) to compare exposure of phantom during dose determination to each subject's exposure.

were exposed to a programmed cumulative midline dose of 1440 rad (14.4 Gy). Monitor dosimeters exposed with the animals indicate that the doses delivered were within 95% of the programmed value.

A similar radiation-exposure program was established for Phase II of the experiment, taking into account the revitalized cobalt source and the requirement of a lower dose of 120 rad (1.2 Gy) for the target penetration dose. For similar exposure rates, distances had to be varied as described in Table A1. All Ss were exposed to a programmed cumulative midline dose of 360 rad. No monitor dosimeters were exposed with the animals, but dosimetry measurements made in primate phantoms confirmed the programmed midline dose.